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VARIABILITY OF TOTAL ELECTRON CONTENT IN THE HIGH-LATITUDE IONOSPHERE FOLLOWING SOLAR MAXIMUM

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13. ABSTRACT (Maximum 200 words)

Northwest Research Associates (NWRA) is recording a database containing measurements of the differential carrier phase (DCP) and the differential group delay (DGD) between the two L-band signals transmitted by satellites of the Global Positioning System (GPS). Data collection is continuing at Shemya, AK, and Hanscom AFB, MA. Software has been, and continues to be, developed to process these data into measurements of trans-ionospheric total electron content (TEC). This database is being analyzed in order to document the variability of TEC and to specify TEC morphology in the region of Shemya, AK. Studies of multipath mitigation and accurate satellite bias determination have been conducted to insure high data quality. Analysis of these and other data developed by NWRA in other high latitude studies in the Shetland Islands, UK, has yielded ionospheric trough boundary signatures. These data will be compared to predictions from available ionospheric models for validation and improvement of the models.

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1. INTRODUCTION AND OBJECTIVES

Ionospheric total electron content (TEC) can significantly affect RF propagation. TEC is defined as the total integrated number of electrons contained in a column of one meter squared cross-section centered on the signal's ray path. Knowledge of ionospheric structure in the region of interest allows for correction of TEC-induced errors.

NorthWest Research Associates (NWRA) is recording a database containing measurements of the differential carrier phase (DCP) and the differential group delay (DGD) between the two L-band signals transmitted by satellites of the Global Positioning System (GPS). Data collection began in May 1992 and is continuing at Shemya, AK, and Hanscom AFB, MA, as solar activity descends from its recent maximum. Software has been developed that processes these data and produces measurements of trans-ionospheric absolute total electron content (TEC). These data, along with existing multi-direction satellite data developed by NWRA in other high-latitude studies in the Shetland Islands, UK, are being analyzed in order to quantify longitudinal characteristics of TEC morphology in the northern mid-latitude and trough regimes of the ionosphere. This database has application to validating and improving ionospheric models for the Shemya region in particular, and the higher latitudes in general.

The first objective of this effort is the generation of a database sufficient to document variability in ionospheric total electron content and related effects due to plasma-density structures, using measurements made at Shemya, AK, and other high-latitude locations. This database is suited to analyses aimed at correcting ionospheric errors that affect the operation of Air Force surveillance systems at high latitudes, specifying TEC morphology in these regions, and developing and validating improved ionospheric models.

The second objective is to develop an assessment of the signature(s) of the ionospheric trough region as viewed by a multi-direction GPS receiver. Data being collected at Shemya, AK, as well as existing data from Shetland Islands, UK, are being used in the assessment. If adequate trough boundary signatures can be found in these data, it may be feasible to develop the capability to monitor the trough boundary in real time using data from the USAF Air Weather Service's new Trans-Ionospheric Sensing System (TISS).

The third objective is the extension of these databases into the declining phase of the solar cycle and the comparison of the data to predictions from available ionospheric models for each region. Such a comparison discloses the accuracy of present ionospheric specifications, permitting definition of approaches for improving models for these specific regions.

To accomplish these goals, NWRA is maintaining and operating, or directing the operation of, receiving equipment at Shemya, AK, and Hanscom AFB, MA. Data were also collected at Thule AB, Greenland during a two week period in November, 1993. The received TEC data are stored on various magnetic media. Software to reduce and analyze the data has been, and continues to be developed.

2. DATA COLLECTION AND PROCESSING

At the halfway point of this 27-month study period, NWRA is maintaining and operating data collection equipment at two sites: Shemya, AK, and Hanscom AFB, MA.

A. Description of Instrumentation

The government furnished equipment (GFE) operated and serviced by NWRA includes the following:

- Stanford Telecommunication, Inc. (STEL) STEL-5010 single-channel GPS receivers,
- Texas Instruments (TI) TI-4100 four-channel GPS receivers,
- Magnavox MX-1502 Transit receivers,
- a National Institute of Standards and Technology Ionospheric Measurement System (NIMS) code-free, multi-channel GPS receiver manufactured by Atmospheric Instrumentation Research, Inc. (AIR),
- a Trimble Pathfinder eight-channel GPS receiver, and
- a NWRA designed and built ITS-10S Transit coherent receiver system (currently intended for deployment to Fylingdales, UK).

The STEL-5010 GPS receiver tracks a single satellite pass for up to six hours. It measures the DGD between the L1 (1575.4 Mhz) and L2 (1227.6 Mhz) signals, the DCP between those two signals, and the received intensities of the L1 and L2 signals from the older Block 1 GPS satellites only. It cannot receive the Block 2 satellites whose L2 signals are encoded such that the GPS selective availability function can be invoked. Except for a two week period in November, 1993 at Thule AFB, Greenland, the STEL-5010 receivers at Thule AB, Greenland; Shetland Islands, UK; and Hanscom AFB, MA; have not been operational during this period due to the large number of hardware failures. Because they can receive only the few remaining Block-1 GPS satellites, it [illegible] considered cost effective to repair these systems.

The TI-4100 four-channel receivers, located at Shemya, AK, and Hanscom AFB, MA, collect data simultaneously from four different GPS satellites, both Block 1 and Block 2. DGD and DCP are recorded at one sample every six seconds. Intensities of the

L1 and L2 signals are not directly measured and therefore scintillation indices, S4, cannot be derived from the TI-4100 data.

The MX-1502 Transit receivers, located at Shetland Islands, UK, and Hanscom AFB, MA, provide latitudinal relative TEC from north-south traveling satellites of the Navy Navigation Satellite System (NNSS). The transmitted signals from these satellites are at 150 Mhz and 400 Mhz. Each satellite pass lasts approximately 15 minutes. In order to determine absolute TEC levels along the satellite track, complementary absolute TEC data is required to calibrate the relative TEC measurements. Absolute TEC information from collocated GPS receivers provides such data.

The NIMS receiver is a code-free GPS receiver whose output is 15-minute averaged values of relative TEC. This receiver is located at Hanscom AFB, MA. In a letter dated 27 July 1992, Mr. David B. Call, president of AIR, Inc., reported that this receiver fails to meet the specified accuracy levels due to a design flaw in the antenna. AIR intends to correct this problem with a redesigned antenna. This redesigned antenna has not yet been received by NWRA, and the receiver is, therefore, not being used.

The ITS-10S receiver, currently located at Hanscom AFB, MA, provides latitudinal relative TEC from the north-south traveling satellites of the NNSS. The fifty Hz sampling rate of this receiver is fast enough to yield scintillation information. Absolute TEC data, available from collocated GPS receivers, is required to calibrate the receiver's relative TEC measurements.

The Trimble Pathfinder multi-channel GPS receiver is currently located at Hanscom AFB, MA. It is capable of collecting data from up to eight satellites simultaneously. The receiver sampling rate is a maximum of two samples per second. Its data output is stored in binary files containing pseudorange, carrier phase, signal to noise ratio (SNR), latitude, longitude, time of week (TOW), ephemeris data, and satellite ID. Its small size makes it suitable as an easily deployable indicator of ionospheric fading.

B. Instrumentation and Operation at Each Site

THULE, DK (GREENLAND)

A 14-day campaign to Thule AFB, Greenland, collected data that is being used to study TEC variation in that region and to test and evaluate the operation of the NWRA ITS-10S Transit receiver and the Trimble Pathfinder GPS receiver. These can be used to supplement a concurrent experiment at Sondrestrom, Greenland. From 4 November 1993 to 19 November 1993, Mr. C. Charley Andreasen (NWRA) operated the Trimble Pathfinder GPS receiver, the ITS-10S Transit receiver, and repaired, reprogrammed and operated the STEL-5010 GPS receiver.

The Trimble Pathfinder GPS receiver system operated without any problems during the entire period. Fourteen days of continuous data were collected and are stored on 4 mm magnetic tape.

The ITS-10S Transit receiver system collected data during this period. Its operation was halted on two occasions when the arctic foxes ate the power cable from the receiver system out to the antenna. The cable was replaced with a less appetizing type, and 11 days of Transit data were recorded on QIC-[illegible] tapes.

The STEL-5010 receiver system was repaired and reprogrammed to record only the L1 amplitude signal at a sampling rate of twenty Hz. Since the L1 signal of all the GPS satellites is not encoded, this change allows the STEL-5010 to track any GPS satellite, not just Block 1. The 20-Hz sampling rate is fast enough to allow the determination of the scintillation index S4 (L1). This test was intended to evaluate the usefulness of the STEL-5010 as a scintillation monitor.

SHEMYA, AK

At the Shemya site, NWRA continues to maintain and direct the operation of the TI-4100 four-channel receiver. The TI-4100 system has been operating reliably from December 92 to the present. DGD and DCP data (absolute and relative TEC, respectively) are being collected. Data quality is very good.

HANSCOM, MA

The ITS-10S Transit receiver system was delivered to Hanscom AFB, MA, on 4 September 1993 and set up for testing. Due to apparent rough handing during shipping and the need for hardware upgrades, Phillips Laboratory (PL) decided to send the ITS-10S back to NWRA in Bellevue, WA, for warranty repair. It was repaired and returned to Hanscom AFB on 14 October 1993. The system operated satisfactorily for a two week period prior to deployment to Thule. During that time, the ITS-10S receiver system's operation was demonstrated to a group of people from the Mitre Corporation [Mitre is on contract to support ESC (Electronic Systems Center) on the project that funded PL to purchase the ITS-10S receiver]. The ITS-10S receiver system is intended for eventual installation at the Ballistic Missile Early Warning System (BMEWS) radar site at Fylingdales, UK.

A TI-4100 four-channel receiver system is in operation at the Hanscom AFB site. It is running the same collection software as the TI-4100 receiver located at Shemya, AK. The receiver experiences intermittent failures, and the data from this site are not continuous. The quality of the data that has been collected appears to be good.

The STEL-5010 receiver is not operational due to equipment failure. The NIMS code-free receiver, as stated before, is awaiting a redesigned antenna in order to meet its

specified accuracy, and is not being operated. The MX-1502 is not operating because there is no defined use for the data at this time.

C. Total Electron Content Data

The DCP and DGD measurement data collected by the TI-4100 four-channel GPS receiver system at Shemya, AK, are stored in a receiver-independent exchange format (RINEX). This format was designed to facilitate the exchange of GPS data by the international geodetic user community. For compatibility with existing analysis and plotting programs, software has been written to convert the RINEX data to single-channel file format.

Initial Shemya data, from days 153-159, 1992, were processed and plotted (see Figure 1). The TEC profiles as predicted by the Bent ionospheric model and generated by RDP, Inc. of Waltham, MA, are shown in Figure 2. These results indicated the need for an assessment of satellite bias and receiver offset values. The DCP data contained discontinuities and required correction. The DGD data were found to have a high degree of multipath contamination.

In order to determine TEC values accurately, the measurement contributions of satellite biases and receiver offset must be considered. Mr. Gregory J. Bishop of Phillips Laboratory at Hanscom AFB, MA, postulated the following method for determining the proper receiver offset and satellite bias values (Ref. 1). First, several days of data were plotted. Data collected from satellites located within one degree of latitude of the site were processed into equivalent vertical TEC and plotted on a 24-hour scale of local time at the ionospheric penetration point (IPP) of the ray path to the satellites. These data should yield a continuous curve that shows the diurnal variation of TEC. Distortion of portions of the curve are attributable to incorrect bias values for the satellites contributing those portions. The receiver offset value affects the overall level of the curve. By iteratively adjusting these quantities and evaluating the plotted results, a set of values can be determined that produces equivalent vertical TEC curves with proper diurnal and seasonal behavior. It was shown that very little change from these empirically derived bias values begins to introduce distortion in the TEC curves, indicating that the accuracy of these values is better than $\pm$ 2 to 3 TEC units (see Figures 3 and 4).

Discontinuity correction of the differential carrier phase data was originally achieved during post processing using Turbo Edit, a commercially available software package. For real time TEC calculations, Applied Research Laboratories of the University of Texas at Austin (ARL-UT) developed a Kalman filter for use with their Real Time Monitor (RTM) software controlling the TI-4100 receiver.

Measurements of the DGD, from which absolute TEC is determined, are very susceptible to contamination by multipath. The DCP is two orders of magnitude less sensitive to multipath effects. It yields a relative measure of TEC, containing a $2n\pi$ ambiguity. The DCP can be referenced to the DGD through the phase-averaging process

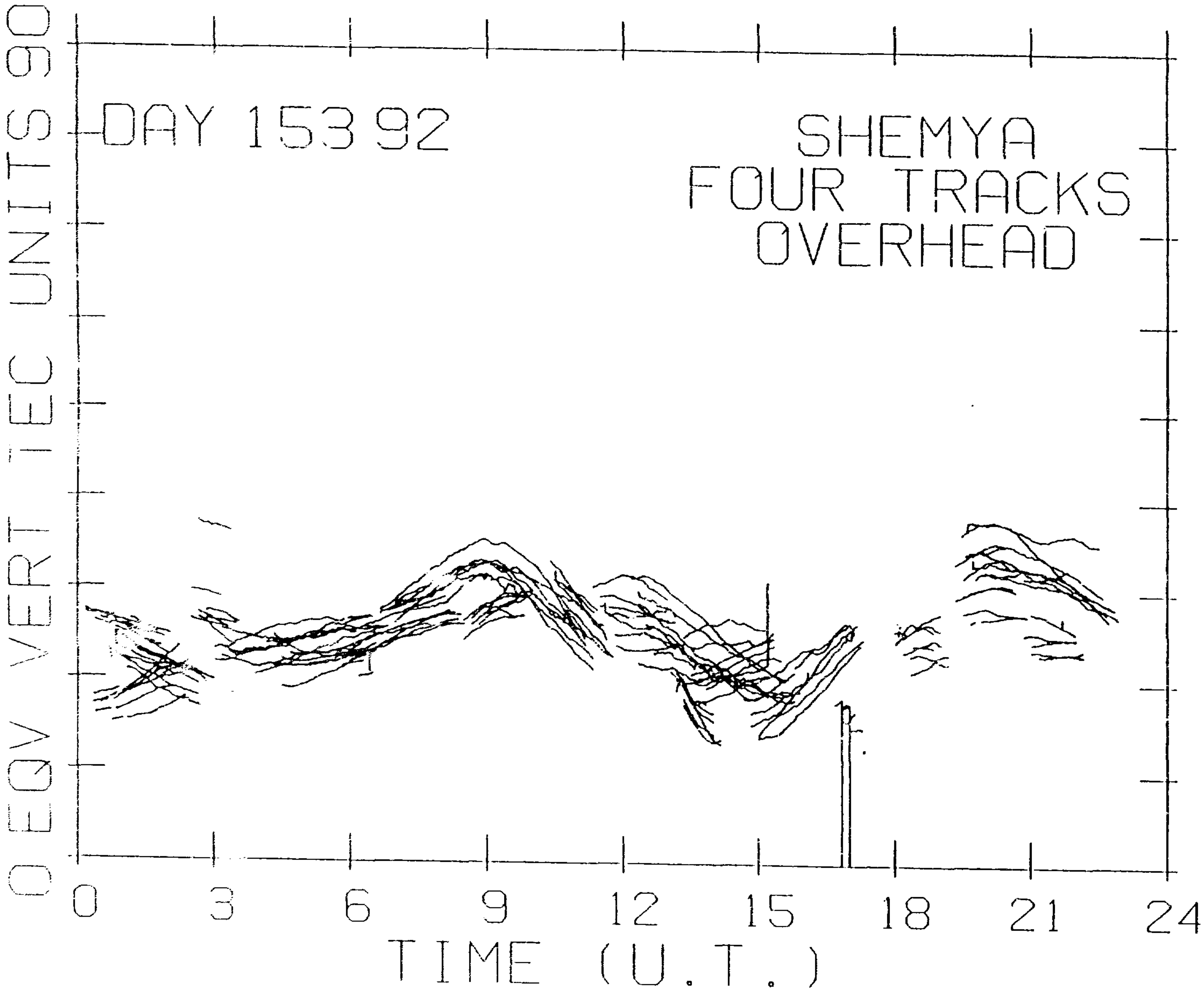

Figure 1. Overplot of Shemya TEC Data from Days 153 - 159, 1992.

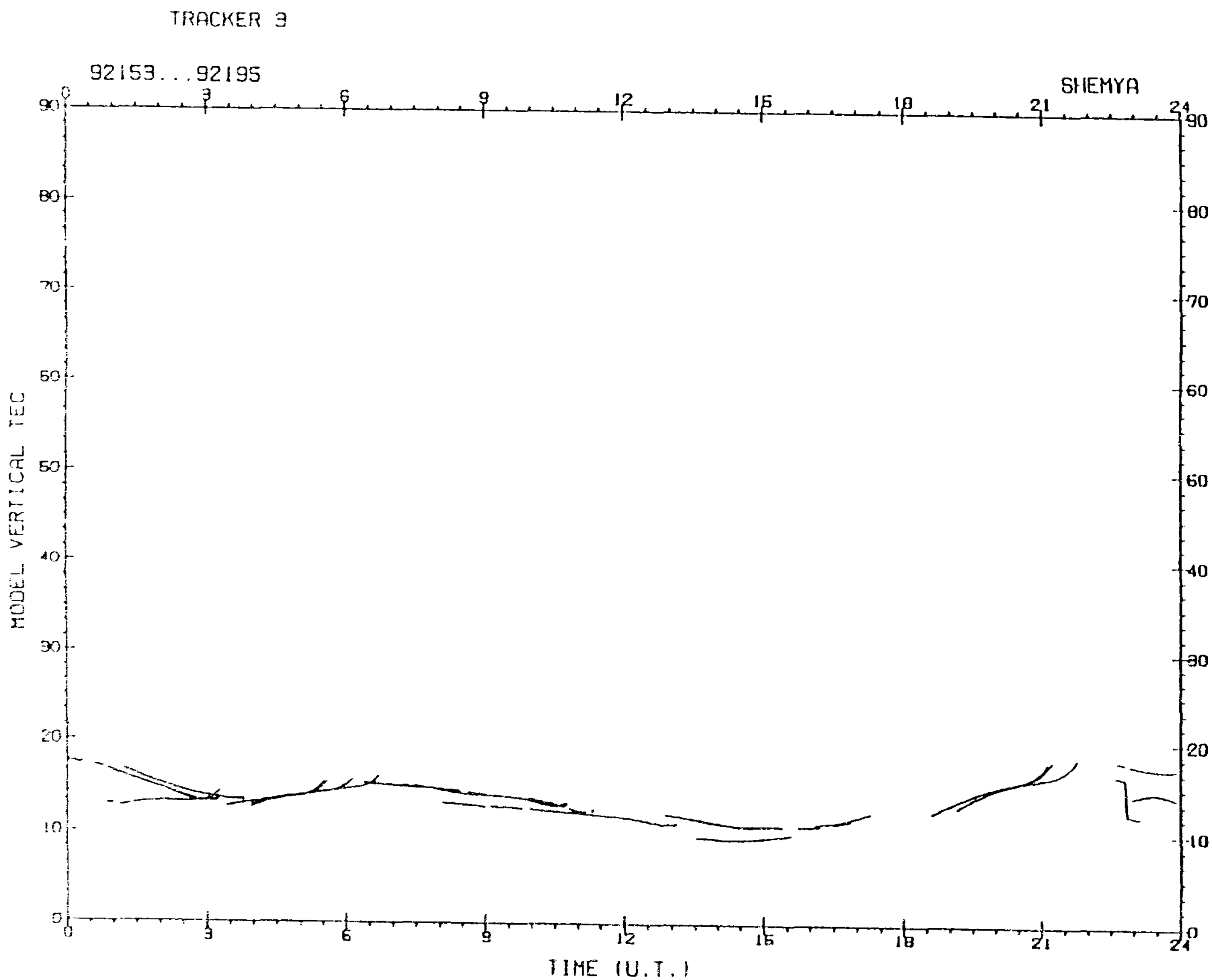

Figure 2. Model-Predicted TEC Behavior at Shemya.

Test of Sensitivity of "Envelope" to Errors in *Receiver Offset*

Shemya Data

2^{+} Months Apart

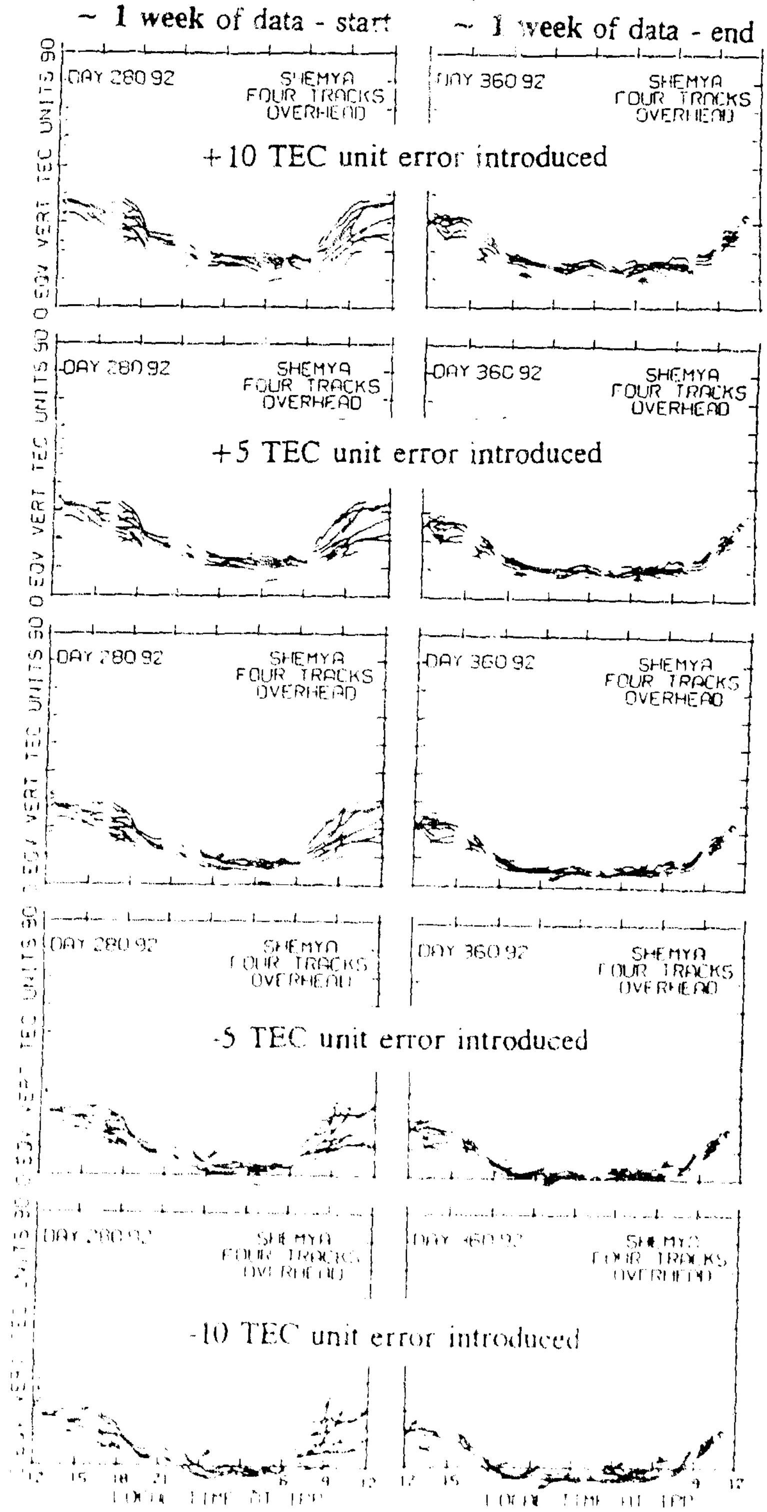

Figure 3. Shemya Data Showing Effect of Changes to Receiver Offset.

Test of Sensitivity of "Envelope" to Errors in T_{GD}

Shemya Data - 2+ Months Apart

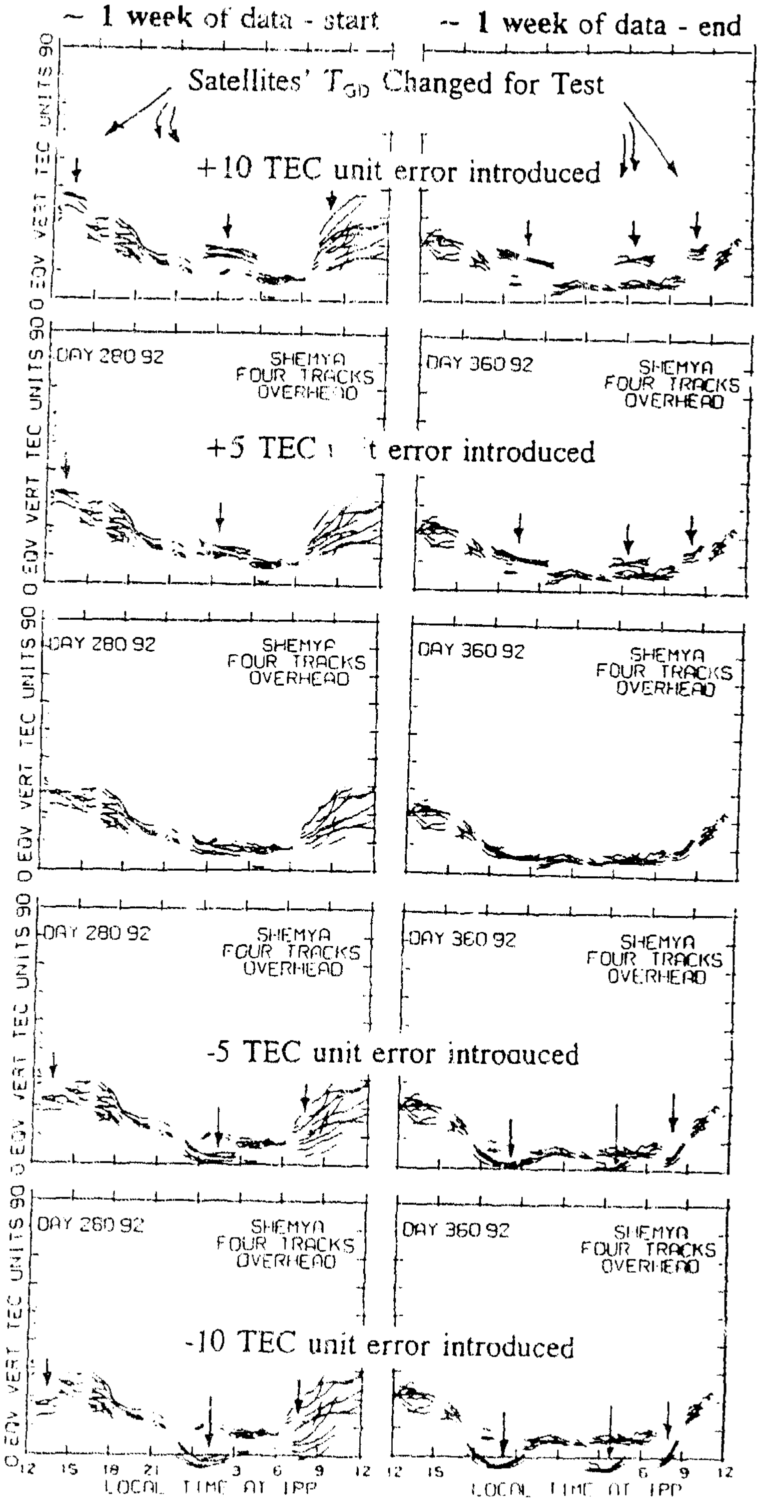

Figure 4. Shemya Data Showing Effect of Changes to Satellite Biases (T_{gd}).

to resolve the ambiguity. The interval of data used for phase averaging must be larger than the period of the multipath, preferably a few hours, or the phase-averaged result will be in error. This is not usually a problem when post processing data, since a GPS satellite pass can last three hours or more, but the error can be very important for real time application.

A software multipath modeling approach proposed by Mr. Gregory J. Bishop of Phillips Laboratory at Hanscom AFB, MA, has been investigated (Ref. 2 and 3). A multipath template is created using 24 hours of off-line DGD and DCP data. The DCP and the DGD containing multipath are phase averaged. The phase-averaged DCP is subtracted from the DGD plus multipath to produce a point-by-point multipath template file. This template contains system noise as well as multipath. To minimize the system noise content, the template is smoothed by taking one-minute averages.

The correlation coefficient for templates from two different days was determined. Results showed that passes containing large multipath were highly correlated, while passes with low multipath had a much lower correlation coefficient. This is understandable since the template contains system noise, which is uncorrelated, and multipath.

A multipath template created from a day of data can be applied to data from subsequent days. Figure 5 shows 24 hours of equivalent vertical TEC from DGD data collected at Shemya, AK. Figure 6 shows the same data after the multipath template created from day 153, 1992, was applied.

Since the multipath template technique relies on daily repetition of the GPS observation geometry, the data and the template must be time aligned to compensate for the precession of the satellite orbits. The template time is shifted 3 minutes 57 seconds for each day that the subject file lags the template file. Using this simple alignment method, a multipath template yields good results for about seven days. A more precise technique based on satellite position alignment promises to significantly increase the effective lifespan of a template.

The spatial decorrelation of a multipath template has been investigated by calculating and plotting the difference in the magnitude of the multipath over a specified spatial distance. The multipath was seen to decorrelate rapidly with spatial distance. It was shown that even a fraction of a degree change in spatial distance resulted in a noticeable change in the template, indicating the dependence of the template on satellite path.

The multipath template technique has been implemented by ARL-UT for use in their RTM software. Data collected by RTM are stored in RINEX format. Since the template is created using data in the single-channel file format, code has been written to convert from RINEX to single-channel format and from single-channel format to RINEX.

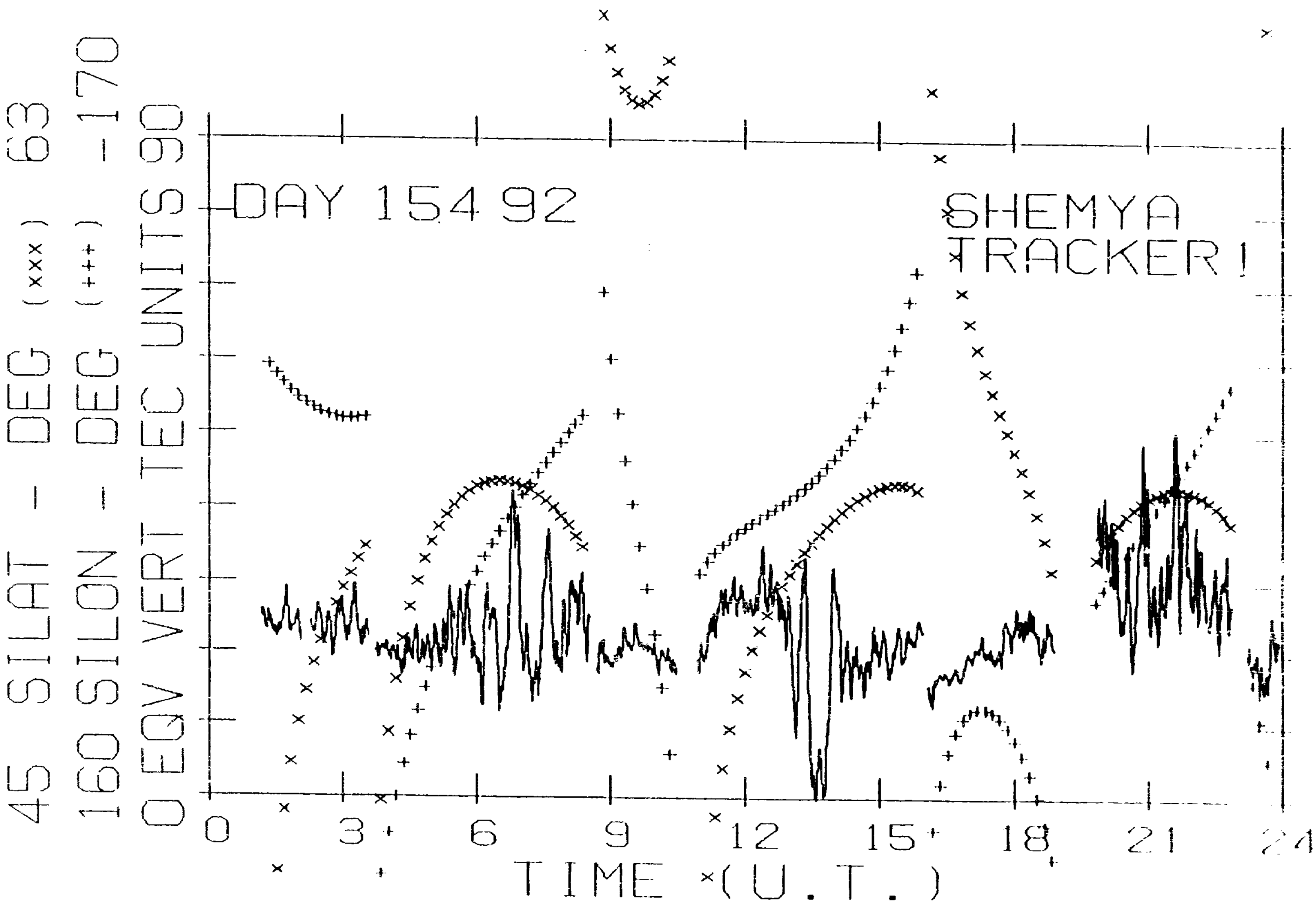

Figure 5. Day 154, 1992 TEC Data from Shemya Containing Multipath.

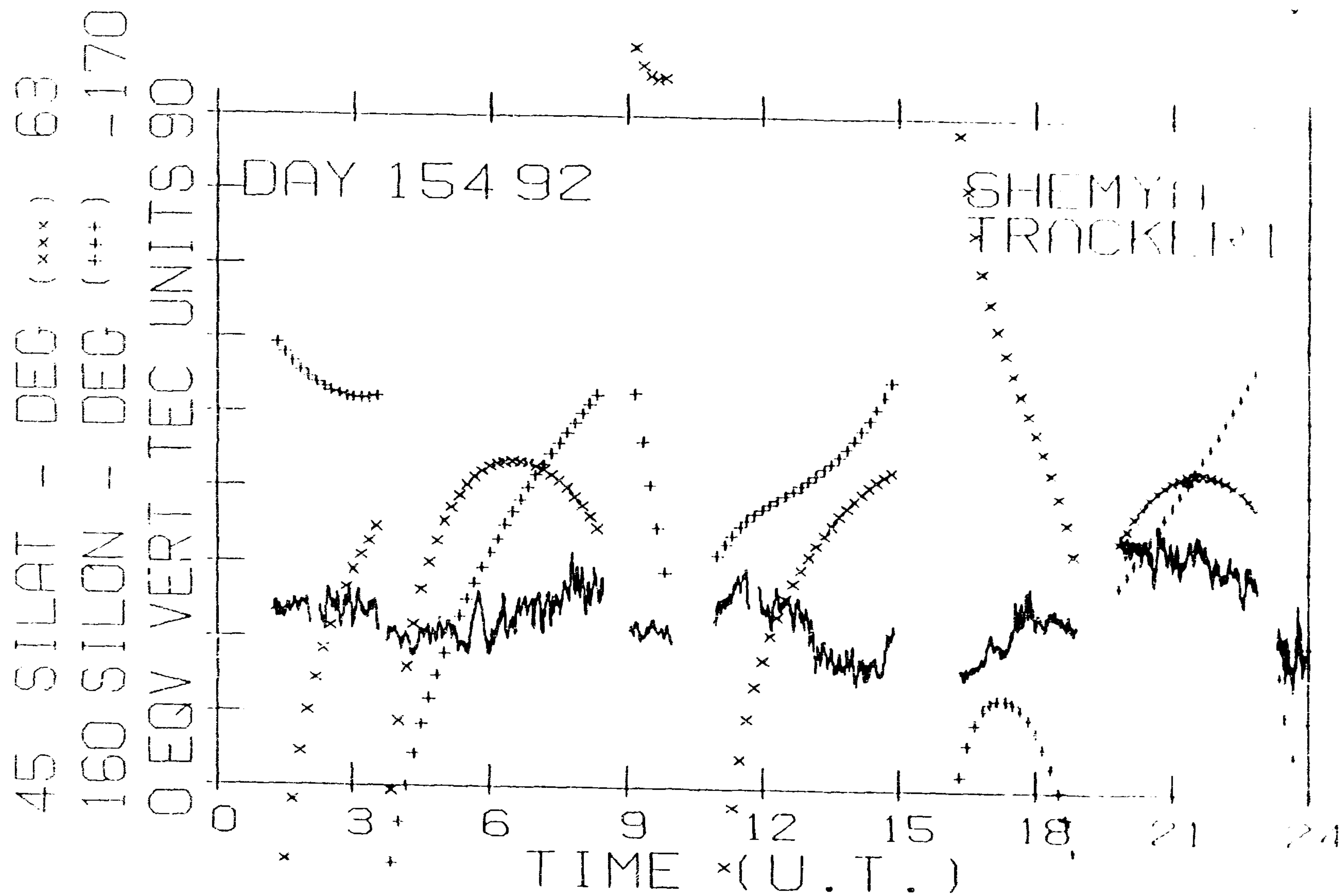

Figure 6. Day 154, 1992 TEC Data After Multipath Template from Day 153, 1992 Applied.

GPS measurement data in RINEX format have been collected with TI-4100 receivers at Shemya, AK, and Hanscom AFB, MA. Data in single-channel format have been collected at Thule AB, Greenland. Access to Jet Propulsion Laboratories' (JPL) substantial RINEX database from many sites worldwide has been acquired. Recently, data collected by Draper Laboratories, Cambridge, MA, using an Ashtech Z-12 receiver [intended for the Trans-Ionospheric Sensing System (TISS) project] have been received by NWRA. With minor modifications to existing programs for handling RINEX data and processing TEC data, all these data can be used to investigate and document TEC morphology.

D. Assessment of Trough Signatures

The trough, a region of lower plasma density in the ionosphere, typically is located poleward of the middle latitudes. It is seen to move equatorward during periods of high solar activity, and its signature is characterized by steepened gradients of TEC. The trough has been seen in some Shetland data from 1991-1992 (Ref. 4). A technique of plotting latitudinally separated data allows viewing of the equatorward movement of the trough, as seen in day 312, 1991, Figure 7. The trough signature is seen overhead (± one degree of the station's latitude) at 1500 hours and to the south of the station at 1630 hours.

Occurrence of the trough is determined by visually inspecting the TEC plots from a station. It may be possible to develop an algorithm that will automatically detect the presence of the trough signature during data processing.

E. Ionospheric Model Assessment

The database being created by NWRA, data collected during earlier efforts, and RINEX data from multiple sources can all be compared to ionospheric model-predicted values of TEC. RDP, Inc., Waltham, MA, has developed analysis software that performs a statistical comparison of TEC values predicted by the Bent ionospheric model, to measured TEC values. Such analysis supports the validation and improvement of existing ionospheric models.

A study is being conducted that will support the validation of the WBMOD scintillation model. Radar data files from the Ballistic Missile Early Warning System (BMEWS) radar at Fylingdales, England, are being analyzed to determine if intensity scintillation (S4) is being seen by the radar. The data are compared to scintillation studies from Transit data collected at nearby Whitby, England, and analyzed by the University College of Wales, Aberystwyth (UCW). Because the radar measurements are at a higher frequency than the Transit measurements, it is necessary to scale the scintillation data for accurate comparison. The scaling is performed according to the WBMOD scintillation model.

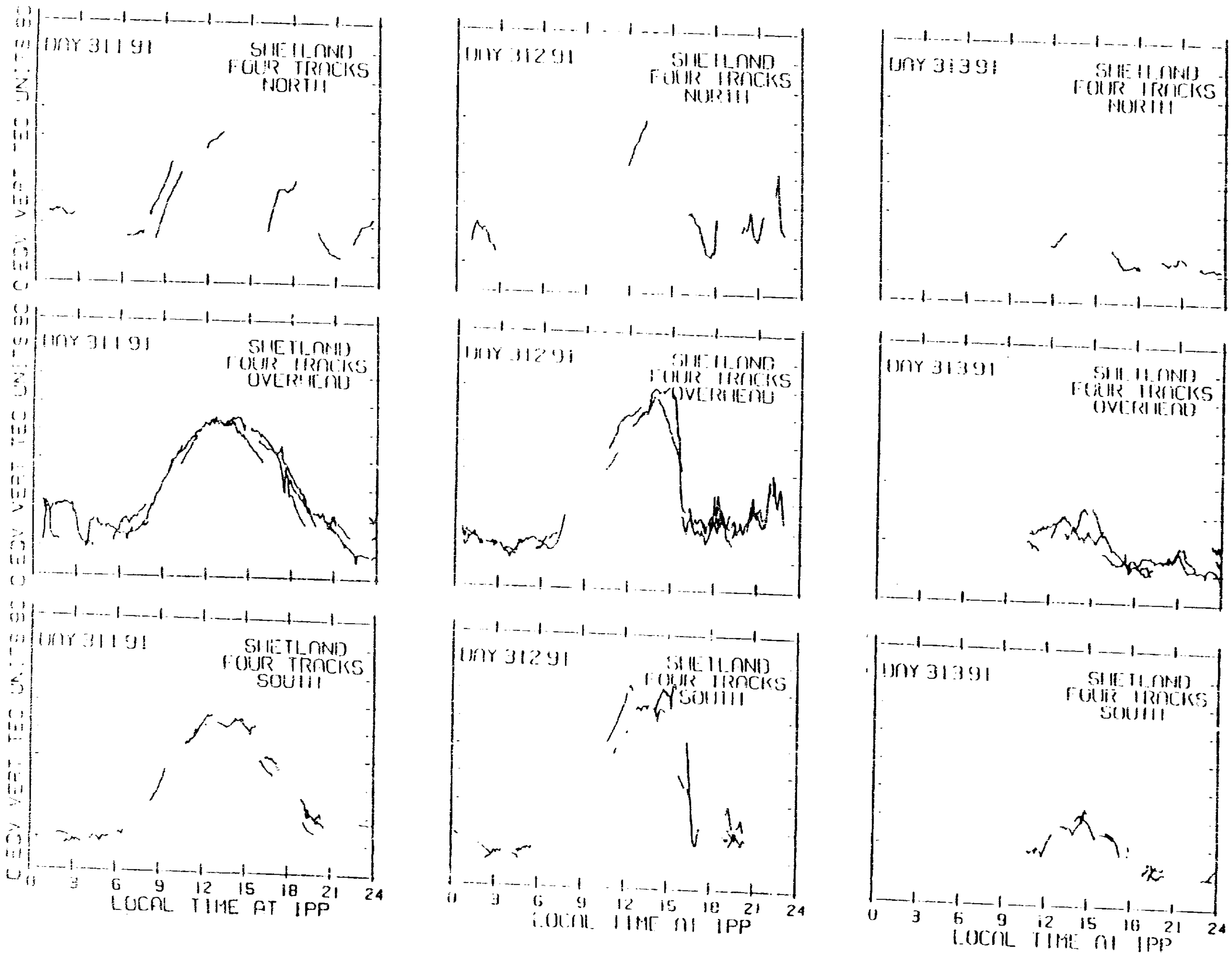

Figure 7. TEC Data from Shetland Islands, UK, Showing Trough Signature on Day 312, 1991.

The radar data are a measurement of a two-way path. Therefore, a scaling must be done so that the values are effectively one-way measurements. Studies have shown that S4 is frequency dependent, and a frequency scaling is performed to translate from the 430 Mhz for the radar data to 150 Mhz for Transit. First, a transformation from significant to weak scatter S4 at 430 Mhz is made. Once in the weak-scatter domain, frequency scaling is applied. (S4 is proportional to $\lambda^{3q/2}$, where q is the one-dimensional power-law index of the irregularities' spatial spectrum.) Then the inverse transformation back to significant scatter is performed.

F. Software Tools Developed for Data Analysis

Software has been, and continues to be, developed to process and analyze data. Programs exit that display equivalent vertical TEC as 24-hour, pass-file, and latitude-specific (north, overhead, and south of the observing station) plots. The multipath content of the data can be analyzed and minimized using existing programs. Code that will allow analysis and plotting of RINEX-formatted data from many sources has been developed and continues to be improved.

G. Database

NWRA has created a database from measurements taken at Shemya, AK; Hanscom AFB, MA; Shetland Islands, UK; and Thule AB, Greenland. In addition to these data, NWRA has obtained access to JPL's substantial RINEX database of GPS measurements from stations around the globe. These data can be processed into a form that is similar to NWRA-collected data for analysis.

3. SUMMARY

Data that have been, and continue to be, collected can be analyzed and displayed as plots of equivalent vertical TEC versus time. The volume of data available provides a valuable resource for characterizing TEC morphology at high latitudes. GPS measurement data from JPL, collected at sites all over the world, supplement the NWRA database. Comparison of measured to model-predicted values permits evaluation of current models for validation or improvement.

Analysis of these data has produced signatures of ionospheric disturbances in the polar cap and sub-auroral European sector and has also yielded ionospheric trough boundary signatures. Analysis of the mid-latitude data from Shemya, AK, has yielded TEC morphology for that region over many months, with diurnal and seasonal variation clearly evident. Final efforts will increase focus on systematizing the data on hand and performing comparative studies of these data to models' predictions.

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